PROCESS SAFETY MANAGEMENT APPLIED TO SCALEUP OF A TRANSFER SYSTEM FOR ELECTROSTATICALLY SENSITIVE MATERIALS

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ABSTRACT

Global Environmental Solutions, Inc. (GES) provides safety management services including helping other companies meet OSHA and EPA requirements applicable to plant processing. GES provides identification and evaluation of hazards, risk control, testing, and documentation control. GES uses a systematic engineering approach to evaluate potential hazards both qualitatively and quantitatively as appropriate.

This paper addresses these techniques and describes their application to determine if large quantities of electrostatically sensitive explosive powders could be safely transferred through a new large-scale mixer feeding system. Electrostatic measurements were taken during laboratory and full scale testing. Charge density measurements were the basis for correlating the subscale and full scale tests. A computer model was developed to determine charging levels where spark breakdown of the electric field could occur. Charge density readings from the full scale tests were used to determine the applicability of the laboratory and computer models. The process was modeled successfully resulting in prediction of general charging trends for the full scale tests. This technique reduced the number of full scale test runs to a minimum. This application of scientific principles to safety related issues can be cost effectively applied to a wide variety of processes to meet plant safety requirements.

INTRODUCTION

The plant process addressed in this paper is part of a large-scale, second generation mixing facility. An extensive process hazards analysis and testing program had been conducted earlier on the original, smaller-scale facility. That work had answered safety concerns for that system. The new process required that large quantities, over three tons, of finely-ground, explosive dry ingredients be fed out of a storage hopper into a mixer. the new transfer systems were similar in design to the older systems but had much larger capacity. The mass effects on charging and electrostatic discharge (ESD) in the new equipment were unknown. The process hazards analysis of the new facility required that the operation be analyzed for the large quantities and a safety margin established for the possibility of high electrostatic charging and ESD initiation of the non-conductive, ESD sensitive material.

As a result of the concern over ESD, a full-scale test was planned to measure the amount of electrostatic charge buildup during ingredient feeding. In preparation for the full-scale test, laboratory testing was necessary to isolate and model some of the electrostatic charging mechanisms which would be seen during the full-scale test.

The objective of the lab testing was to model the electrostatic charging characteristics of the dry ingredients. The ingredients tested were ammonium perchlorate (AP), a fine, semi-conductive, mild explosive powder, and cyclotetramethylenetetranitramine (HMX), a fine non-conductive, high explosive powder. AP is moderately sensitive to ESD initiation. HMX is extremely sensitive to ESD initiation. From the results of the lab-scale tests, correlations could be made to predict the level of charging which would be reached in the full-scale test. The full-scale test would finally be run with the less ESD sensitive AP to verify the predictions made from the lab-scale tests, If the predictions were accurate, then the full-scale testing would continue with the more sensitive HMX. This approach to the full-scale test would reduce the number of full-scale runs to a minimum,

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
AUG 1996		**00-00-1996 to 00-00-1996**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Process Safety Management Applied to Scaleup of a Transfer System for Electrostatically Sensitive Materials	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Global Environmental Solutions, Inc, ,4000 South 8400 West,Magna,UT,84044**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM000767. Proceedings of the Twenty-Seventh DoD Explosives Safety Seminar Held in Las Vegas, NV on 22-26 August 1996.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**18**	

limiting personnel exposure and limiting the facility down time for testing.

HAZARDS ANALYSIS METHODOLOGY

The GES hazards analysis methodology is in conformance with OSHA 29 CFR 1910.119. The GES methodology consists of three analysis phases:

I. Process Assessment
II. Design Hazards Analysis (DHA)
III. Operating Hazards Analysis (OHA)

In the process assessment phase of a hazards analysis, information is gathered on the process design, process flow, equipment, and hazardous materials involved. In the Design Hazards Analysis, techniques such as logic diagrams (fault tree) and failure modes and effects analysis (FMEA) or other analysis techniques are used to identify and address potential hazards in the process design. The Operational Hazards Analysis is conducted during the startup and initial operation phase of the process when equipment and procedures are essentially in place. Throughout the process hazards analysis phases, recommendations and requirements are imposed to make changes if potential hazards are discovered. GES uses a form called a Safety Action Request (SAR) to provide a closed loop means to assign responsibility to correct potential problems and to provide documentation of action completion. The GES methodology is outlined below.

The Process Assessment is a compilation and review of the Process Safety Information section of OSHA 29 CFR 1910.119. Completion of the DHA and OHA constitutes compliance with the Process Hazards Analysis section of OSHA 29 CFR 1910.119. The proposed EPA regulation, 40 CFR Part 68 has similar process hazards analysis and documentation requirements. The process hazards analysis work described in this paper was part of the operational hazards analysis conducted during the startup and initial operation phase of the process. In this case, because of the electrostatic properties of the dry ingredients, it was considered necessary to conduct a quantitative hazards analysis comparing the in-process ESD energy available in the system with the ESD sensitivity of the process ingredients.

GES HAZARDS ANALYSIS METHODOLOGY OUTLINE

I. PROCESS ASSESSMENT
- A. GATHER INFORMATION
  - 1. DESIGN & FACILITY REVIEWS
  - 2. PROCESS FLOW
  - 3. EQUIPMENT
  - 4. HAZARDOUS MATERIALS
  - 5. PROCEDURES
  - 6. NORMAL/ABNORMAL CONDITIONS
  - 7. WHAT AT RISK
- B. DEFINE SYSTEM
- C. DETERMINE HAZARDOUS TOP LEVEL EVENTS (HTLE)

II. DESIGN HAZARDS ANALYSIS (DHA)
- A. DEVELOP LOGIC DIAGRAMS
- B. HAZARDS REQUIRING CONTROL
  - 1. FIRE/EXPLOSION
  - 2. INJURY/DEATH

3. PRODUCT DAMAGE
4. FACILITY/EQUIPMENT DAMAGE
5. ENVIRONMENTAL DAMAGE

C. FMEA (OTHER HAZARDS ANALYSIS TOOLS USED WHEN APPLICABLE)
D. RISK CATEGORIES
E. RECOMMENDATIONS

III. OPERATIONAL HAZARDS ANALYSIS (OHA)
A. OPERATIONAL HAZARDS EVALUATION
1. PROCEDURES
2. EVENT/MISHAP HISTORIES
B. DETAILED ENGINEERING ANALYSIS
1. PROCESS POTENTIALS
2. EQUIPMENT SAFETY FACTORS
3. HUMAN FACTORS
4. HAZARD RISK ASSESSMENT
5. MATERIAL CHARACTERIZATION
C. HAZARDS SUMMARY (SAFETY FACTORS AND PROBABILITIES)

D. DOCUMENT RECOMMENDATION COMPLETION

TRANSFER SYSTEM ESD ANALYSIS CONDUCTED DURING OHA

IV. FOLLOW-UP
A. VERIFY PROCESS
B. ADDRESS CHANGES
C. RESOLVE AUDIT ISSUES
D. REVISIT ANALYSES

PROCESS DESCRIPTION

The ingredient feed system consists of the following components:

1. Bin dumper
2. Feed hopper
3. Vibratory tube feeder
4. Vibrating screen
5. Batch mixer

The ingredients were dumped from a storage bin into the feed hopper. From the feed hopper, the material fed into the vibratory tube feeder, this in turn fed into the vibrating screen. After passing through the vibrating screen, the material entered the feed chute and slid into the mixer. See Figure 1.

THEORY

For electrostatic charging to occur, dissimilar materials must come in contact and then be separated. This contact and separation causes one material to have excess electrons, i.e., a negative charge, and the other materials to be electron deficient, i.e., a positive charge. This transfer of electrons is know as the Triboelectric Effect. The extent of this electron exchange is determined largely by the location of the two materials in the Triboelectric Series. Materials toward the top of the Triboelectric Series have a propensity to lose electrons while the materials toward the bottom of the series tend to gain electrons.

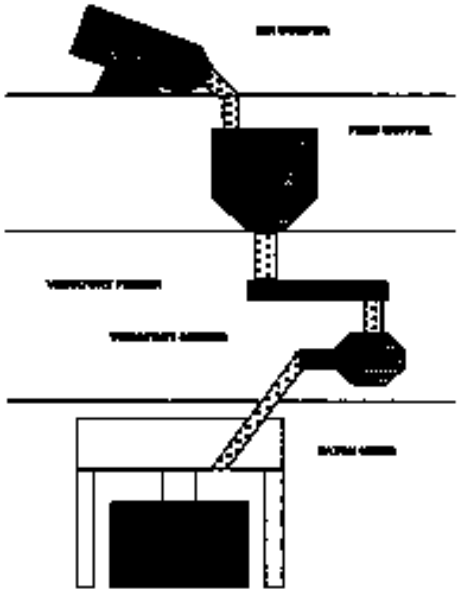
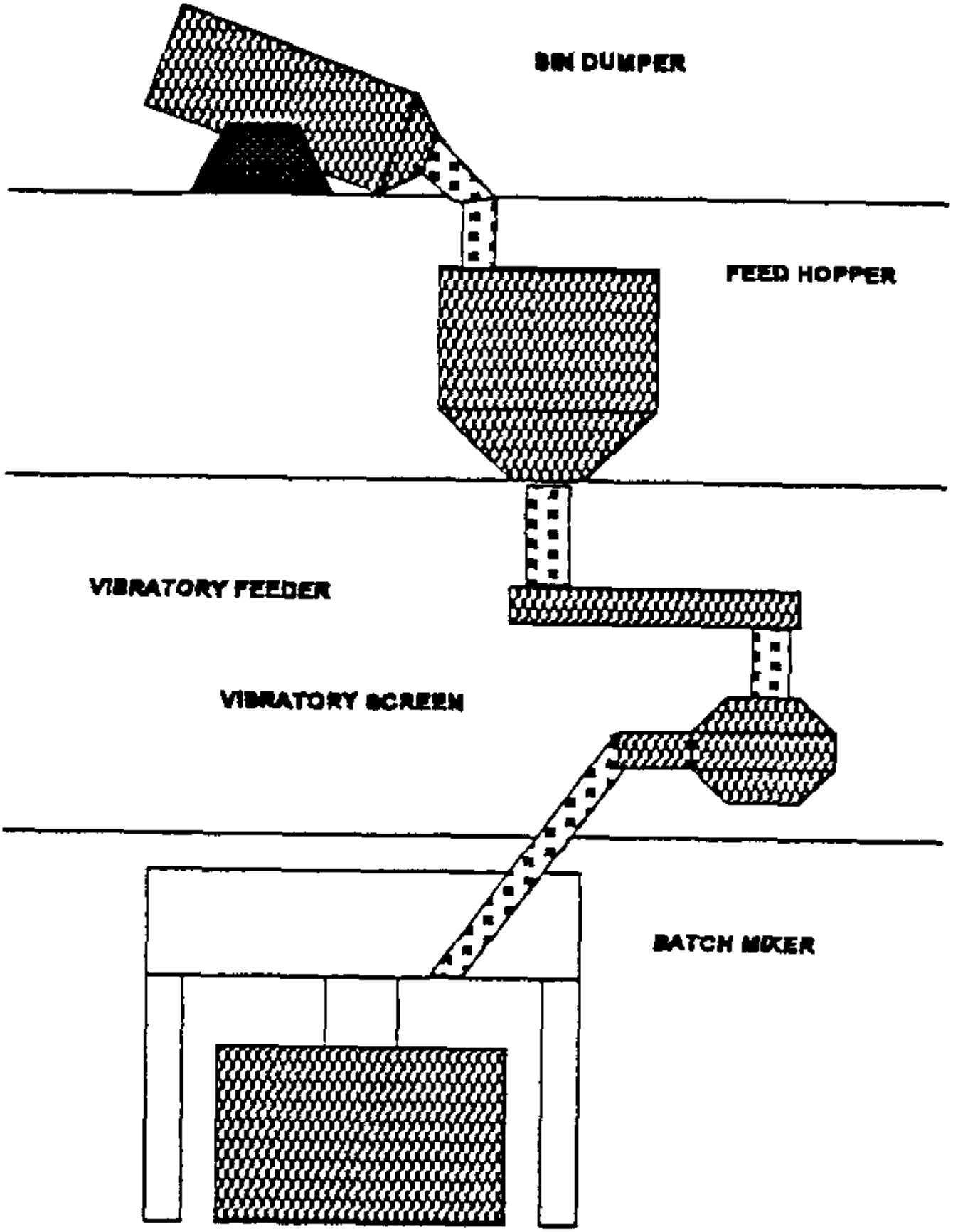


Figure 1 Schematic of the multilevel feed system

In the case of this test, the grounded stainless steel feed system provides an infinite electron source. The materials to be used in this test were low on the Triboelectric Series and therefore gained electrons upon contact with the grounded stainless steel. Fine powders enhance electron exchange because of the large surface area and because of the large number of contacts and separations which occur over the grounded stainless steel surface. Application of this theory to fine powder flow would indicate that the controlling factor for charging is material contact with the grounded surface area, and the residence time of the material on the grounded surface, i.e., flow rate. When the system is dirty, i.e., the surface is coated with a powder layer, the contact between the bulk powder and the grounded surface is limited resulting in lower charging than would be seen in a clean system.

From previous tests it has been shown that the flow characteristics of the materials to be used in this test change as the feeding mechanisms change. For example, while feeding powder through a vibratory feeder, the bulk of the powder rides on a layer of particles in direct contact with the stainless steel surface. This results in minimal charging of the bulk material. In the areas of the feed system where sliding occurs the flow characteristics depend largely on feed rate. At low powder flow rates the individual particles follow a circular pattern where they ride on the top of the bulk, fall across the face of the bulk, then proceed underneath the bulk. This rolling or tumbling action causes mixing and repeated surface contact and separation, as feeding occurs.


BIN DUMPER
FEED HOPPER
VIBRATORY FEEDER
VIBRATORY SCREEN
BATCH MIXER

At high flow rates the bulk of the powder rides on a powder layer next to the surface resulting in minimal mixing. With these flow characteristics and electrostatic charging experience, the following predictions can be made:

1. Minimal charging should be seen through the vibratory tube feeder at the proposed flow rates.
2. Minimal charging should be seen at high flow rates during sliding.
3. The highest charging should be seen during sliding at low flow rates.
4. The highest charging is expected in a clean system.

EXPERIMENTAL

The electrostatic charge testing technique used for this test was first applied at Hercules by L. A. Losee for the initial electrostatic evaluation of HMX type processing equipment.[1] The original test method was enhanced by the addition of digital data acquisition, data manipulation and remote electric field measurements.

The instrumentation setup is designed to measure streaming current between the ingredient bulk and electrical ground. This is achieved by electrically isolating the receiving vessel using the Faraday cage technique. By inserting an electrometer between the bin and electrical ground the streaming current can be measured. See Figure 2. The definition of electric current is:

$$I = \triangle Q / \triangle T \qquad (1)$$

Where I is the electric current in amperes, Q is the charge in coulombs, and T is the time in seconds. As the change in Q and the change in T become very small (i.e., as the limit of Q, $T \rightarrow 0$) then:

$$I = dQ/dT \qquad (2)$$

Separating the parts results in:

$$dQ = I\,dT \qquad (3)$$

Integrating both sides gives:

$$\int dQ = \int I\,dT \qquad (4)$$

or:

$$Q = \int I\,dT \qquad (5)$$

Equation (5) states that the integral (or area under the curve) of a current versus time trace will yield the charge, Q, of the system. In both the lab test and the full scale test the output from the electrometer was recorded by a digital oscilloscope where it was stored on floppy disk. The current versus time record was integrated on the oscilloscope to get the total charge Q.

One way to determine the amount of charge on a powder during feeding is to measure the charge density. The charge density, $Q^{\wedge}$ (Coulombs/Kilogram), can be determined by taking the total charge Q, as calculated in Equation (5), and dividing this value by the weight of material fed. It has been determined from past testing with HMX that electrostatic discharge will not occur below a certain charge density. This value was used as a cut off point, above which full scale testing would be stopped. While this method is very conservative, it ensures that no incendiary discharges will occur.

When high charge density is coupled with a semi or non-conductive material and a grounded vessel, a charge gradient, or electric field, is created between the material and the vessel wall. Monitoring the electric field has the advantage that it provides an immediate indication of the process charging conditions. Computer modeling can also be used which will enable charge density to be calculated from the field strength.[2] This technology is useful in situations where electrical isolation of the components is not practical.

LABORATORY TESTING

The tests performed in the laboratory examined several modes of charge generation. These modes were material sliding down an inclined chute, material moving through a vibrating tube, and material passing through a vibrating screen. The slide down an inclined chute studied the effects of area, flow rate, and different materials of construction on the charge density readings. The materials of construction studied were: (1) 304 Stainless Steel and (2) Aluminum.

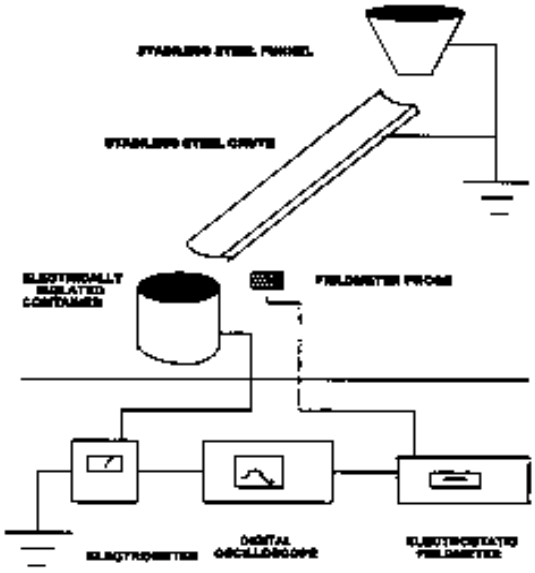


Figure 2 Schematic of the laboratory slide test

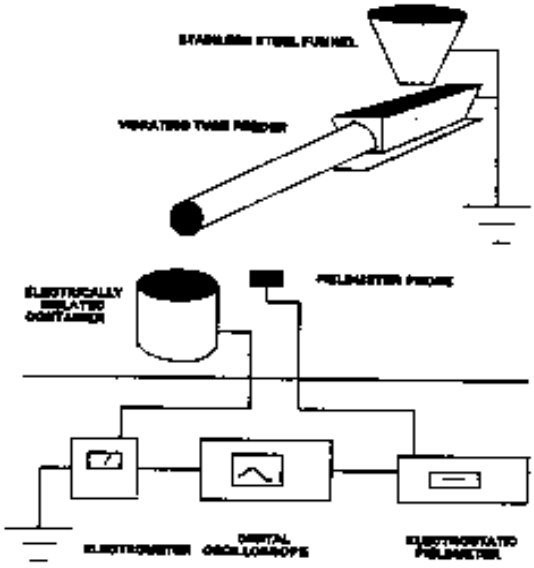


Figure 3 Schematic of the laboratory vibration test

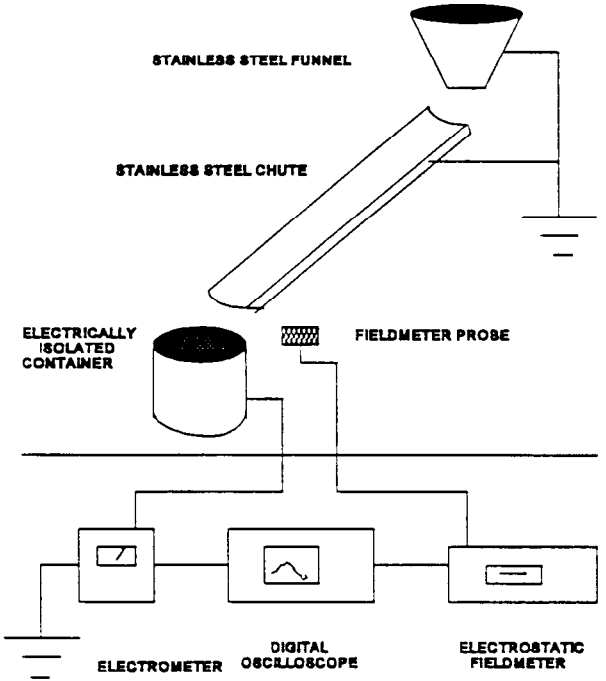
The vibrating tube experiments studied the effects of area and flow rate on the overall charge density reading.

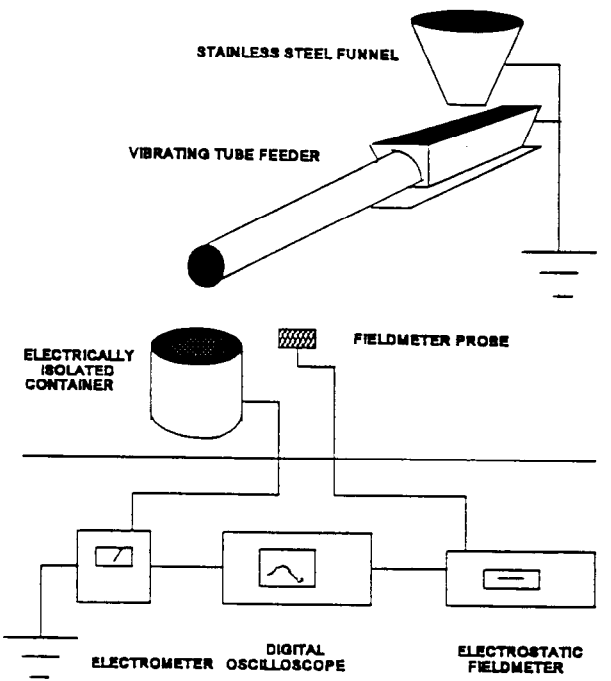
The material flow rate and the contact surface area were the variables of interest in the laboratory testing. The flow rate was divided by the contacted surface area of the transfer system to define the variable $m^{\wedge}$ (Kg/sec cm^2). The new variable, $m^{\wedge}$ was used to make the results independent of the system size.

Each of the charge generating modes tested required a slightly different test apparatus and setup. However, the same variables were measured and the same techniques used in each of the tests.

Inclined Chute Slide Test

The inclined chute test used two different materials of construction, stainless steel and aluminum. The


STAINLESS STEEL FUNNEL
STAINLESS STEEL CHUTE
ELECTRICALLY ISOLATED CONTAINER
FIELDMETER PROBE
ELECTROMETER
DIGITAL OSCILLOSCOPE
ELECTROSTATIC FIELDMETER


STAINLESS STEEL FUNNEL
VIBRATING TUBE FEEDER
ELECTRICALLY ISOLATED CONTAINER
FIELDMETER PROBE
ELECTROMETER
DIGITAL OSCILLOSCOPE
ELECTROSTATIC FIELDMETER

stainless steel test setup was a length of 7.62 cm (3") diameter stainless steel pipe which had been cut in-half lengthwise, see Figure 2. The aluminum test setup was a length of 8.9 cm (3½") aluminum pipe.

Each test setup was individually fastened to a laboratory stand with a catch pan at the bottom. A funnel was placed above the setup to aid in the feeding. The funnel and the slide setup were electrically bonded together and then grounded to an earth ground. The pan was electrically isolated using .64 cm (¼") nylon blocks. The resistance between the pan and ground was greater than 10^{12} ohms. When electrical isolation had been verified, a coax cable was connected to the pan and the electrometer in order to measure the streaming current.

Vibrating Tube Test

The vibrating tube was a laboratory size ERIEZ magnetic tube feeder of stainless steel construction. A funnel was placed above the tube feeder in order to aid feeding. See Figure 3. The funnel and the tube feeder were electrically bonded together and then connected to earth ground. A pan was placed at the exit of the tube feeder. The pan was isolated using .64 cm (¼") nylon blocks. When isolation was verified, the pan was connected to the electrometer via a coax cable. The feed rate was controlled by varying the amplitude of vibration. The surface area was varied by adding on extensions of different length stainless steel tubing to achieve tube lengths of 19-, 25-, and 31-inches.

Screening

Based on the findings of Glor[3] that screening, or sieving, ranks lowest of charge generating modes, in-depth testing of the screening operation was not done. Previous work at Hercules Bacchus has shown that material exiting a screening operation is less charged than the material entering. Because of time constraints, this phenomenon was not further investigated.

Equipment

The following electronic equipment was used during the lab and full scale tests:

1. Monroe Field Meter model 171
2. Keithley electrometer
3. 3M model 703 static meter
4. Nicolet digital oscilloscope model 4094

The Monroe field meter allowed for remote monitoring of the electric field on the charged powders. The electrometer was used in the ammeter mode to measure the streaming current. The 3M static meter was used for spot checks of the voltage on the powder. The Nicolet was used for digitally recording the data and for data reduction.

DISCUSSION OF LABORATORY TEST RESULTS

The results from the sliding tests are contained in Figures 4-5. Figure 4 shows the results of using different materials of construction for the slide test. The difference in charging using the stainless steel and the aluminum was indistinguishable.

For the laboratory testing, the apparatus was wiped clean after each test run. This was intended to stimulate the worst case condition, i.e., during startup when the feed system would be clean. The results of the slide testing show a relationship between the charge density and the feed rate, and between the charge density and the surface area of the pipe contacting the powder.

The results from the vibrating tube studies are shown in Figures 6-7. The feed tube was wiped clean of powders after each run. Again simulating the worst case condition of a clean feed system. Because of the cohesive nature of fine HMX, it was difficult to obtain consistent charge density readings at the same m^. This accounts for the data scatter as shown in Figure 7. However, these results show the same general trend between charge density, flow rate, and the surface area of the tube feeder in contact with the powder.

The full scale test predictions were based on the work done in the laboratory. Knowing the surface area of the test set up and the range of flow rates, it was possible to make conservative predictions of the highest charge densities which would be expected in a clean system. It should be noted that the first run in the full scale test was expected to produce the highest charging because of the clean system. Subsequent runs were expected to produce variable data, below the predicted values, because the surface conditions of a coated system are constantly changing.

For convenience, charge density was plotted as a function of feed rate in the full scale test predictions. The predictions, see Figure 8, were the sum of the charge due to vibratory feeding and the charge due to sliding. The anticipated charging fell at or below acceptable charge density levels.

FULL SCALE TESTING

As discussed earlier, the mix building transfer systems contain each of the feed mechanisms tested in the lab, a vibrating tube, a vibrating screen, and a long steep slide. The slide length for this test was longer than usual because a chute extension was used to connect the feed chute to the receiving bin. This modification was made because it was infeasible to electrically isolate the mix bowl. See Figure 9. The extra slide distance was taken into account when making the full scale charging predictions.

The same test techniques that were used in the laboratory testing were used in the full scale test. The problem with the charge density approach to measuring charge buildup is that if high charging occurs it cannot be detected until after the transfer takes place. For this reason, a cut off level for the surface voltage in the receiving bin was established. If this cut-off was reached during the test, the transfer would be stopped and the charge allowed

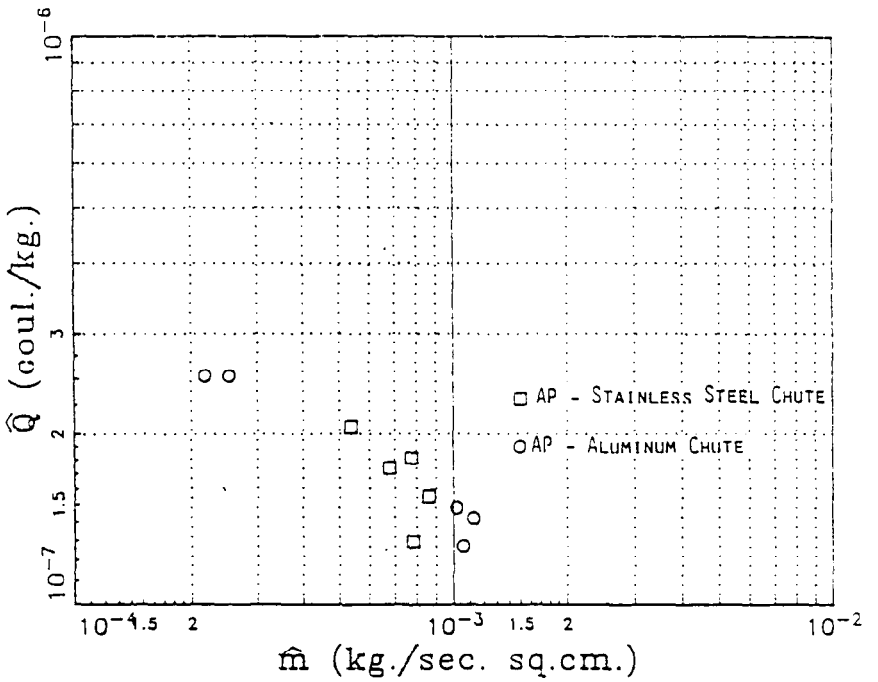


Figure 4 Graph of the AP slide data. The two slide surfaces studied were aluminum and stainless steel The difference in materials had no measurable effect. (Surfaces wiped clean between runs.)

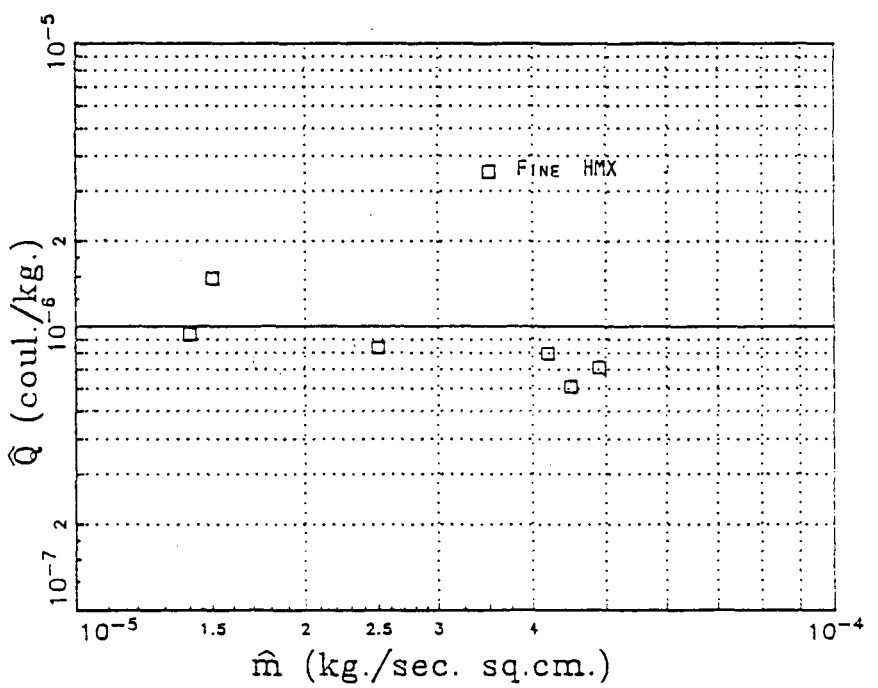


Figure 5 Graph of the HMX slide data. The slide surface was stainless steel. (Surfaces wiped clean between runs.)

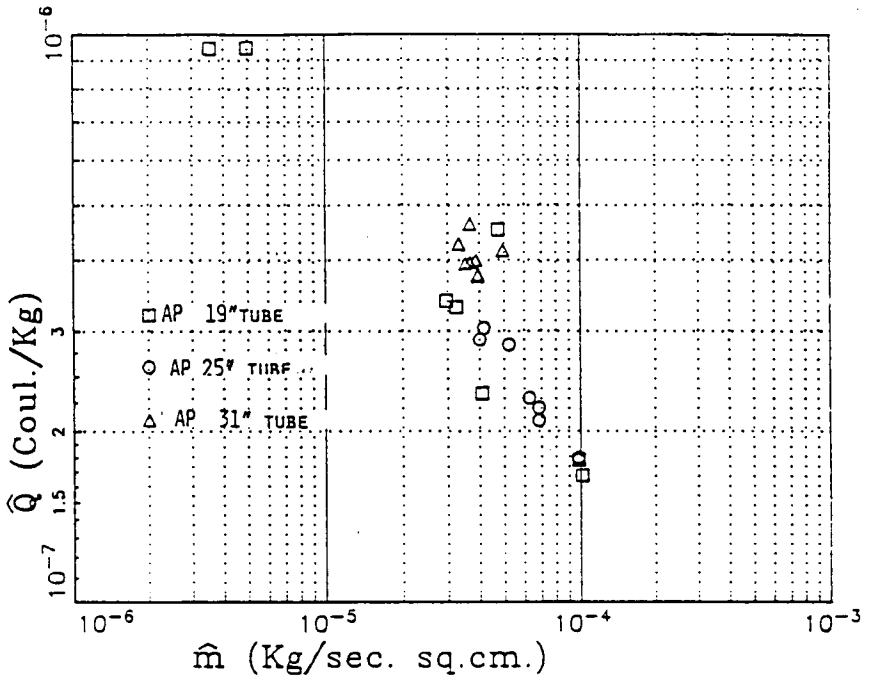


Figure 6 AP vibratory feeding data. Three different lengths of tube are used. The trend indicates that in a clean system, higher feed rates result in lower charge density readings. (Surfaces wiped clean between runs.)

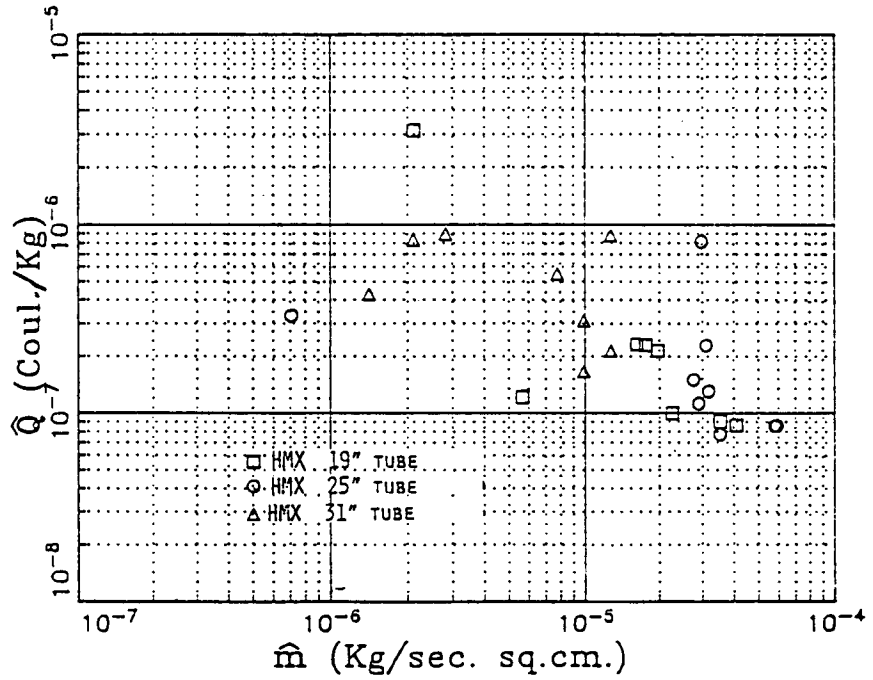
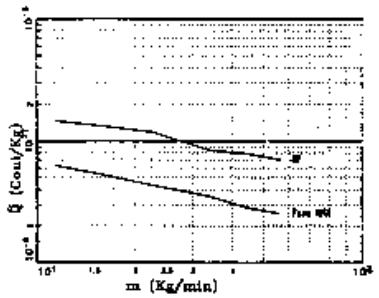


Figure 7 HMX vibratory feeding data. Three different lengths of tube are used. The trend indicates that in a clean system, higher feed rates result in lower charge density readings. (Surfaces wiped clean between runs.)



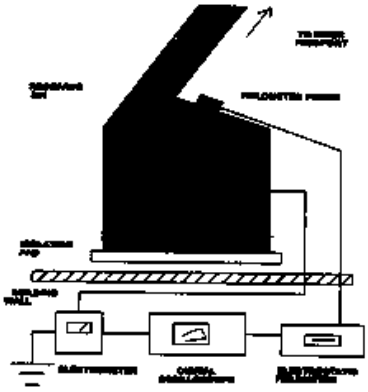


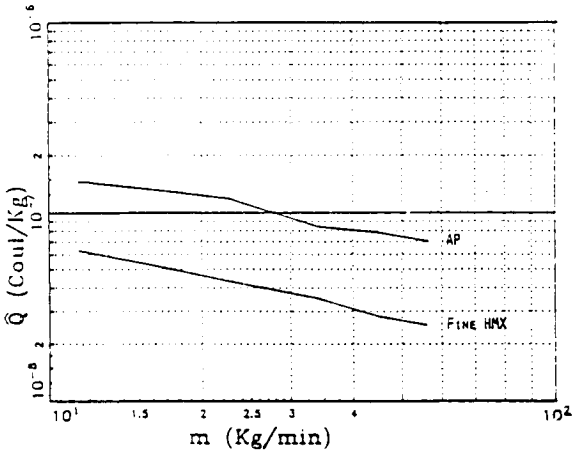
Figure 8 Full scale test predictions for AP and HMX. represent the maximum charge density expected at various feed rates.

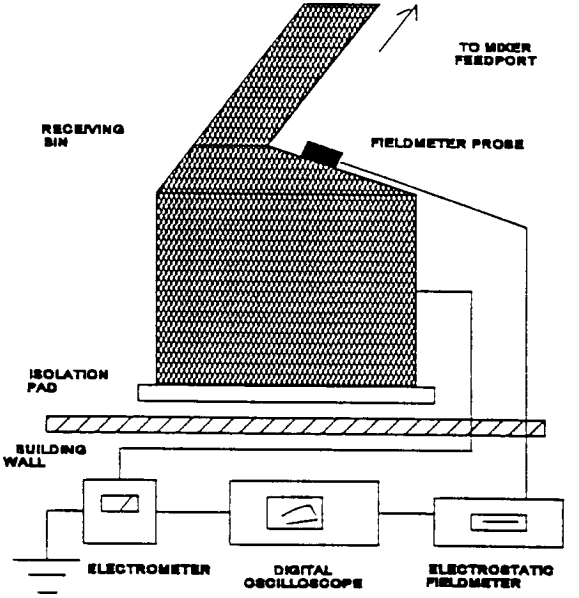
Figure 9 Schematic of the full-scale test set up The Predictions electronic equipment configuration is shown.

to dissipate. The measurement of the surface potential was accomplished using an electrostatic field meter. The probe for the field meter was placed in the receiving bin. The meter itself was placed outside of the building. Due to the geometry of the vessel, it was necessary to calibrate the field meter readings to know surface potentials in the particular geometry of the receiving bin.

The full scale test used a fine grind of AP. There were two grinds of HMX, a coarse and a fine grind both smaller than 20 micron. By working from the least to the most sensitive ingredient, if a high charging problem were detected it would be with the less sensitive ingredient. AP is considered to be the least sensitive of the ingredients tested; therefore, it was used for the first series of tests. The fine grind HMX is more prone to charging and is the most sensitive to ESD initiation; therefore, it was tested last.

The testing was run at various feed rates which were controlled by a process control system. Variables such as feed rate and kilograms fed were recorded by computer. The electric field strength and the current versus time trace were recorded at the test site. The on-site recording equipment was monitored with a remote camera so that excessive charging could be detected before critical levels were reached.


10^{-6}
2
10^{-7}
2
10^{-8}
$\bar{Q}$ (Coul/Kg)
AP
FINE HMX
10^{1}
1.5
2
2.5
3
4
10^{2}
m (Kg/min)


TO MIXER FEEDPORT
RECEIVING BIN
FIELDMETER PROBE
ISOLATION PAD
BUILDING WALL
ELECTROMETER
DIGITAL OSCILLOSCOPE
ELECTROSTATIC FIELDMETER

DISCUSSION OF FULL SCALE TEST RESULTS

The data from the feed study testing is reported in Figures 10 and 11. The flow rates reported are the average values recorded for a given run. There are several runs which have more than one feed rate. This is because the feeders are equipped to run in a normal or a dribble mode.

Figure 10 represents the data taken while feeding AP through the feed system. The highest charge destiny recorded was 5.6E-08 Coul/kg. The lowest charge density recorded was 1.5E-08 Coul/kg. The surface voltage on the material in the receiving bin did not exceed 8,000 volts and the highest recorded electric field was 20 volts/cm.

Figure 11 represents the data taken while feeding coarse and fine HMX. The highest charge density recorded for the coarse and fine material was 3.0E-08 coul/kg and 6.8E-09 Coul/kg respectively. The lowest charge density recorded for the coarse and fine material was 2.1E-09 Coul/kg and 1.8E-09 Coul/kg. A polarity reversal was noticed between the coarse and fine grinds for HMX. The reason for this reversal has not been determined. However, these results are consistent with previous work. The surface voltage on the material bed in the receiving bin did not exceed 13,000 volts for the coarse material and did not exceed 8,000 volts for the fine material. The highest recorded electric field was 270 volts/cm for the coarse material and 110 volts/cm for the fine material.

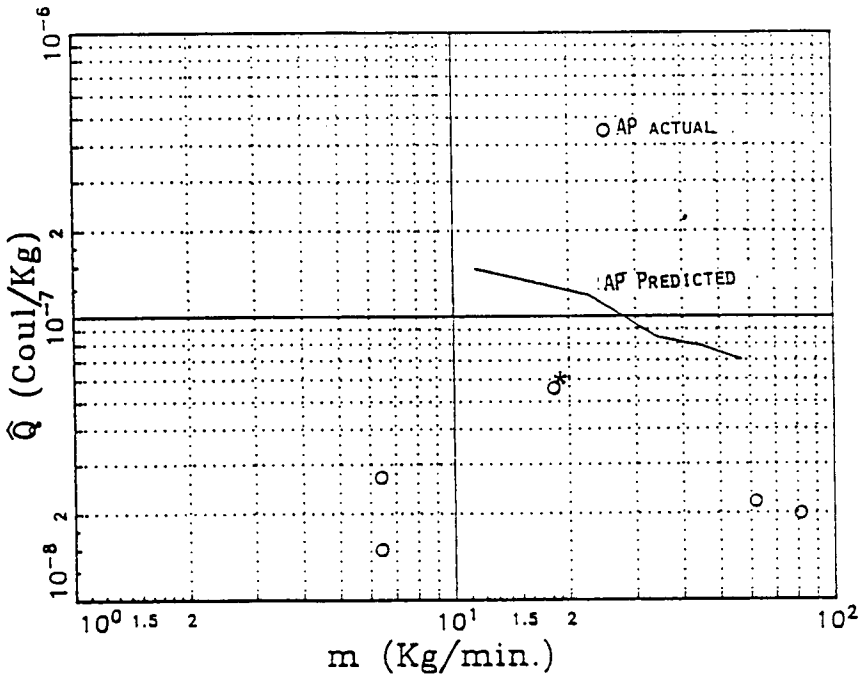


Figure 10 AP predicted vs. actual charge density readings. The solid line represents the maximum predicted charging expected during AP feeding.
*** The feed system was clean fefore this run.**

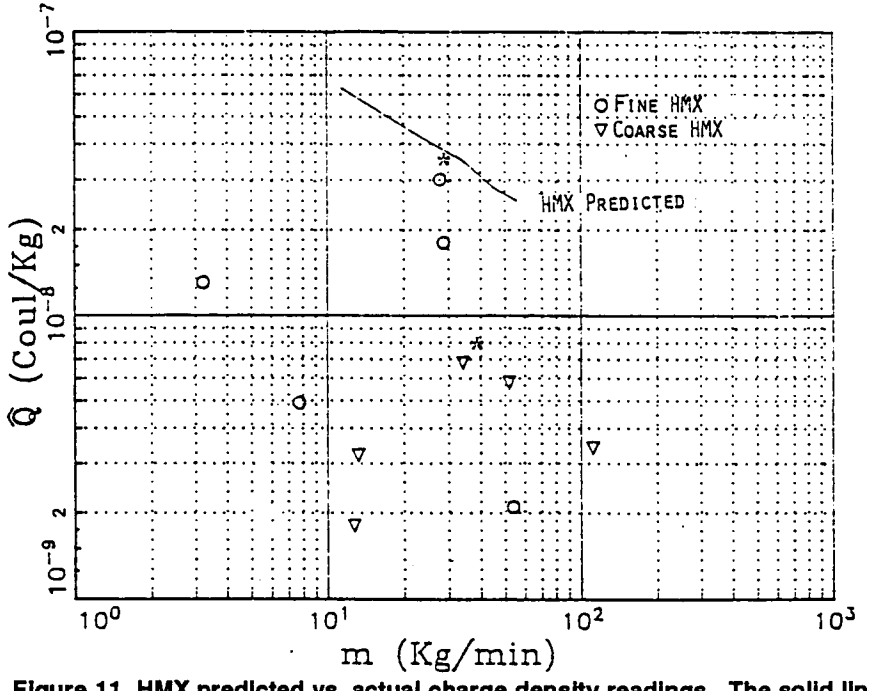


Figure 11 HMX predicted vs. actual charge density readings. The solid line represents the maxomum predicted charging expected during HMX feeding.
*** The feed system was clean before this run.**

AP

Prior to the full scale test it was decided that this material would be used to determine the accuracy of the charge density predictions. Figure 10 displays the actual and predicted charge density values for this material.

The charge densities measured for this material while feeding into the receiving bin were lower than the predicted values. The charging characteristics at moderate to high feed rates, 25-115 kg/min, followed the same pattern established during the laboratory work i.e., as the flow rate increased the charge density decreased. In contrast to the model, the charge density at low flow rates, less than 25 kg/min, were among the lowest recorded, see Figure 10. A possible explanation for this occurrence is that when the system is dirty, at lower flow rates, the bulk of the material resides on a layer of material which has adhered to the tube wall, instead of riding on the tube wall itself. This material layer acts as an electrostatic insulator and prevents the bulk of the material from coming in contact with a grounded surface. At higher flow rates, greater than 25 kg/min, it is postulated that the higher material flow keeps the tube wall relatively clean, resulting in consistent charge density readings for any given flow rate.

HMX

Coarse. The coarse material was fed through the feed system at various feed rates. No charge density predictions were made specifically for the coarse material since the fine material was considered to be the worst case. The coarse material followed the same charging pattern established with AP, i.e., followed predictions at low flow rates favorably. Variations between the predicted and actual charge density values can be explained as above for the AP runs.

One difference which was noted on the coarse material is that it charged positively rather than negatively, like AP. Apparently the surface conditions on the coarse grind cause the material to change position in the Triboelectric Series.

Fine. The first run with fine HMX resulted in the highest charge density recorded. This value agreed with the predictions made from subscale test, 1.2E-06 (Coul/kg) predicted vs 9.3W-07 (Coul/kg) actual. See Figure 11. The subsequent runs were below the predicted charge density values. Fine HMX failed to exhibit the charging trend established with coarse HMX and AP. This is due in part to the cohesive nature of fine HMX. Once the material had coated the tube walls, it was not easily knocked off. This is similar to the phenomena observed with coarse HMX and AP, at low flow rates i.e., the material bulk rides on a layer of material which is adhered to the surface. This material interaction tends to reduce charging because there is less contact and separation between the dissimilar materials, i.e., the powder and tube wall.

SUMMARY AND CONCLUSIONS

The results of this work are considered unique to the transfer system and materials studied. Charge density and the electric field would be different for variations in system size or configuration and materials. However, it has been shown that charge density predictions for large systems can be made based on laboratory work.

The laboratory work examined a very well defined transfer system. The transfer system was modeled by three different modes of charge generation which were studied separately. Of the three modes studied, sliding down an inclined chute provided to be the largest charge generator. Vibratory feeding was next and the effects of screening were considered negligible. The predictions were the sum of the charge due to vibratory feeding and the charge due to sliding.

The laboratory work saved a great deal of time and limited the amount of personnel exposure to explosives during the full scale test. The parameters examined in the laboratory experiments provided accurate scale up predictions for the full scale test. The contacted surface area of the transfer system and the flow rate of the powder were the parameters used to scale up from the laboratory work. The flow characteristics of the

powder changed with flow rate and feeding impetus. When the walls of the transfer system became coated with a thickness of powder, charge density readings were lower than the predicted values. When the walls of the transfer system were kept clean, charge density readings were as predicted.

Based on past data, modeling, and actual tests, excessive charging is not a problem in this transfer system during normal process operations. However, a problem could exist with fine HMX at low flow rates in a clean system. Recommendations were made to minimize the risks when starting up a clean system. Unnecessary cleaning of the system are avoided. The results of the full scale test were used to justify operating the new process.

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